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FINAL REPORT
HYDRODYNAMICS OF TURBOMACHINES

Fluid Dynamics Branch
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by

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FINAL REPORT

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I. Introduction. This report concludes the work carried out in the general field of hydrodynamics of turbomachines under Contract Nonr 220(24). The objective of the present report is to indicate the scope of the work carried out, to outline in brief the reports and publications issued, and to review current work in progress that has not yet been reported.

II. Objectives. The principal objectives of this work have been to understand the basic features of the flow in various types of turbomachines and where possible to use such results in the development of design theories. Turbomachines are complex fluid devices and it would not be possible to consider all aspects of the real fluid flow within them. Instead, attention has been focused upon a few important problems and types of machines and flows of a rather limited nature. The major emphasis was placed upon problems of cavitation in axial machines and certain theoretical as well as experimentally related phenomena.

In flows complicated by cavitation, experimentation is a necessity and accordingly heavy emphasis was placed upon it. However, the facilities needed for this research were not particularly expensive. Basically, three experimental projects were undertaken. The measurement and observation of cavitating flows in axial inducer pumps, the observation of cavitation and cavitation inception in fluids other than water, and the observation and measurement of forces on the vanes of a cavitating cascade in a water tunnel. With the exception of the latter task, the principal findings of these programs have all been reported as in Table I.

In what follows a brief description of the several results found will be given. They are grouped into three general categories: experimental work in cavitating axial flow inducers, some properties of cavitation in other than tap water, and experimental and theoretical work in both fully wetted and cavitating cascades.

Cavitating Inducers. Many conditions of operation result in extensive cavitation within the rotors of pumps and turbines. Generally the occurrence of cavitation is promoted by high fluid velocities and relatively low ambient pressures. Both of these conditions prevail in turbopumps for missiles, for example. As it is usually considered a desideratum to have small light weight components of turbomachines, cavitation can be a problem in any liquid system. An interesting application where such considerations are paramount is that of pump-jet propulsion for high speed ships.

A small experimental apparatus was built to observe the flow characteristics and to make measurements of overall head, flow rate and efficiency during cavitation. This flow circuit consisted of a tank containing approximately 35 gallons on which a circular test section, two inches in diameter, was placed. The flow was recirculated through auxillary pumps if needed and flow rate measuring device before being returned to the stilling tank. The axial inducers were thus approximately two inches in diameter and had a hub diameter of one inch. The inducers were driven by an externally mounted d.c. motor. The housing was of transparent plastic so that the flow and the cavitation could be seen. Provision for measuring velocity profiles and flow angles downstream of the rotor was also made. This apparatus was used extensively and a number of experiments on axial inducers of various types and the flow patterns exterior to them were carried out as described in 1, 2, 3, and 4 of Table I.

Briefly it was found that while there were appreciable real fluid and tip leakage effects, the magnitude of the cavitation number near breakdown could be estimated from free-streamline theory for flows of tap water. Various regimes of cavitation flow patterns were found and among these one of the most interesting is one in which an oscillating non-steady (perhaps propagating) flow pattern develops. The occurrence and existence of non-steady flow oscillations occasioned by cavitation seems to be a characteristic feature of cavitation in turbomachines and as recent work has shown, in isolated hydrofoils and cascades as well (16, 17, 18 and 20). Nevertheless, many aspects of the cavitating flows in such machinery still remain obscure. Of these, the question of proper scaling laws for cavitating flows with fluids having various properties and with possibly various amounts of dissolved gas remains as one of the most important to be determined and the literature of this subject is rapidly growing at the present time.

Cavitation Scaling. To gain some insight into the mechanics of cavitation scaling with various fluids, a small recirculating tunnel having a transparent glass working section one inch in diameter was assembled. The special features of this small tunnel were that the upstream stilling section was quite large - large enough to install a vapor pressure bomb containing the circulating fluid. Heat exchangers and pressurization equipment were externally provided. Operating temperatures could range from room temperature to 250°F. One object of the experiments was to measure the difference in pressure between the vapor pressure in the vapor pressure bomb and the pressure within an established cavity. A manometer to measure the anticipated small pressure differences was also mounted within the upstream stilling section. Cavitation was formed behind a sting mounted disk supported from upstream. A pressure orifice opening to the rear of the disk communicated the cavity pressure to one side of the manometer within the stilling section. In this way the pressure difference at various temperatures between the cavity and vapor pressure of the bulk fluid could be determined. Although all precautions were taken to minimize any errors arising from non-uniform temperatures and the pressure orifice was protected from splash, it was very difficult to obtain consistent readings. It should be mentioned that prior to the actual taking of a reading, the connecting lines between the orifice and the manometer were purged to vacuum. The general trends of the results were that for water, the cavity pressures were slightly higher than vapor pressure when the water was at room temperature - a well known fact in water tunnel cavitation studies - and the cavity pressure became lower than the vapor pressure when the bulk temperature exceeded about 180°F. The higher cavity pressures found with room temperature water are attributable to the dissolved air coming out of solution; at the higher bulk temperatures approaching 200°F, the cavity pressure being lower than the vapor pressure can be ascribed to a thermal sub-cooling of the evaporating liquid as suggested in (8).

Similar tests with a fluorinated hydrocarbon "Freon 113" which has a normal boiling point of 117.6°F were largely unsuccessful owing to the virtual impossibility of removing the dissolved air from the liquid in the vapor pressure bomb. The reference pressure then of the liquid in the vapor pressure bomb was thus determined to a great extent by air content rather than by temperature alone. It was observed, however, that the appearance of the cavity behind the disk was appreciably different in the "Freon" as compared with the water experiments. See (6, 7). From these observations it is concluded that parameters which scale properly the cavitation phenomenon in different fluids or perhaps for the same fluid at different temperatures will have to include the transport properties of the fluids and that the configuration of the cavity flows must be known before deductions regarding which physical parameters are important can be made. This program was interrupted by the construction of the Kármán Laboratory and experimental work has not been resumed.

<u>Cascades.</u> An infinite row of equally spaced vanes - or cascade, as it is called - is often considered as an element of a complete turbomachine; theories and experiments for such flows are used in the designs of many

types of axial flow machines, primarily pumps, turbines, compressors, and so forth. Linearized free streamline theory is applied to the choked flow past a cascade of circular arc hydrofoils in (9), to the partial cavitation in cascades of flat plate hydrofoils in (15), and an exact non-linear calculation is made for partial cavitation in a cascade of flat plates of semi-infinite chord (12, 13). The latter calculation permits estimates of loss coefficients due to cavitation to be made. These are useful in determining the performance of cavitating inducer pumps.

Flow measurements are made in (14) of the flow through an axial flow pump of very low blade-height chord ratio in which the blades themselves subtend an angle around the hub of nearly 90 degrees. The results of these measurements are that even for such a "helical" vane the concept of a cascade is applicable, and the measured lift coefficients and lift-slope values agree reasonably well with cascade theory.

The physical characteristics of cavitation in a cascade of hydrofoils have not yet been fully determined; neither for that matter have all the aspects of the real cavity flow past an isolated hydrofoil been treated, though recent experimental efforts have been directed along this line (16, 17, 20). From the investigations to date it appears that partial cavitation (i.e., when the region of cavitation is less than the chord) on an isolated hydrofoil is basically an unsteady phenomenon. Most of the experiments carried out in the present work on cavitating isolated hydrofoils have been with cavitation starting at the leading edge of plano-convex hydrofoils. As the ambient pressure is reduced the cavities lengthen until they are approximately one-half chord long. Instabilities appear then to develop and the cavity with somewhat further reduction in pressure commences to oscillate in a regular fashion during which the end of the cavity moves from a point near the nose to the trailing edge. A sufficient reduction in pressure causes the cavity to become longer than the chord and the oscillation then disappears; "super-cavitation" may then be said to occur. The characteristics of these unsteady flows are most interesting and as they cause relatively large unsteady forces to be exerted on the hydrofoil and surrounding structure, their study is believed to be quite important.

As mentioned above, relatively little information is available on the characteristics of cavitating cascades. Indeed, facilities in which such experimentation can be conducted are exceedingly rare, and at the present time only the cascade tunnel of Professor Numachi at the University of Tôhoku, Sendai, Japan, has published results on partial cavitation in cascades. A feasibility study was carried out to determine if cascade tests could be made in the two-dimensional working section of the high speed water tunnel at the Hydrodynamics Laboratory. It was decided that over a limited range of stagger angle and flow turning such tests could in fact be made. The working section was modified to provide a stream 60 percent of the present inlet height of the tunnel. Adjustable walls downstream of the cascade were provided so that the flow could be turned the amount required for proper cascade operation. The adjustable wall section terminated abruptly in the inlet portion of the existing two-dimensional diffusor to form a submerged jet. Five vanes were used in the cascade and the force on the central vane was measured by the water tunnel force balance. The vanes were cantilever mounted and individually adjusted to the angle desired. The nominal stagger angle was 45 degrees, the spacing of the vanes 3.2 inches, the chord 4 inches, and the span of the vanes 6 inches. The maximum flow turning (due to geometric limitations of the working section) was about 10 degrees. The vanes used were plano-convex hydrofoils of 8 percent thickness.

Both fully wetted and cavitation experiments were carried out. The experimental procedures and principal findings are outlined in (19).* In short, it was found that when the flow was fully wetted the experimental results agreed reasonably well with the theory - as well as did the results on isolated hydrofoils of the same profile shape.** The agreement was even better, however, for a turbine cascade than for a pump cascade.

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*Now in preparation for publication.

**This portion of the experimental work on cascades was partially supported under Contract N123(60530)34767A.

Little data exist for comparative purposes for the cavitating flows. Unlike prior experiments it was possible to "choke" the cascade section. That is, cavities formed free jets the full length of the test section. Under these conditions, the forces and flow turning tended to approach the theoretical values predicted for a fully cavitating flat plate cascade. The actual conditions of the flow are not precisely those of flat plate cavitation but the agreement is considered satisfactory.

The non-steady oscillatory processes observed on the isolated hydrofoil cavitation experiments were found to occur in cascade as well. A short film strip[18] is available which shows this phenomenon and also gives some idea of the physical scale of the tunnel.

Finally, we would like to mention an as yet uncompleted project, the computation of hydrofoil characteristics in slightly non-plane flows. Often, in fact usually, hydrofoil profile sections and cascades are not in a strict two-dimensional plane flow. The mean flow may be accelerated or retarded by curved flow boundaries. As an example, the flow through a turbomachine may speed up because of a contraction of the cross-sectional area. As a result the flow through a cascade - or hydrofoil - cannot be considered strictly two-dimensional. The results of two-dimensional plane flow analyses and experiments cannot be applied directly to such flows without further consideration. A study has been made of a rather simple "quasi-two-dimensional" flow. It is assumed that an otherwise uniform rectilinear flow of constant velocity is confined in a channel of gradually varying height. The through flow velocity within the passage therefore varies inversely with the height of the channel. It can be imagined that bodies such as hydrofoils span the passage. In plan form, the flow appears two-dimensional as usual but because of the slowly changing distance between the walls of the channel the flow is not a strict two-dimensional flow and, for example, the velocity varies from one wall of the channel to another. It may be shown, however, that if the variation in channel height is slow, an averaged velocity potential and streamline function for incompressible irrotational flows can be defined which satisfies the equations

$$\phi_{xx} + \frac{h_x}{h}\phi_x + \phi_{yy} = 0$$

and

$$\psi_{xx} - \frac{h_x}{h}\psi_x + \psi_{yy} = 0$$

respectively where h, the channel height, is assumed to change only with x. The average velocity components over the channel height are

$$u = \phi_x = \frac{1}{h}\psi_y$$

$$v = \phi_y = -\frac{1}{h}\psi_x$$

The case of a channel whose breadth increases linearly with x is seen to reduce to that of axi-symmetric flow. An exponential channel given by $h = h_o \exp \gamma x$ results in a particularly simple case to treat. The fundamental solution for a vortex, for example, becomes

$$\psi = \frac{\Gamma}{2\pi}\exp\frac{\gamma x}{2} K_o\left(\frac{\gamma}{2}\sqrt{x^2 + y^2}\right)$$

where Γ is the circulation and K_o is the modified Bessel function of the second kind. A source solution can be likewise found and with these the flows about arbitrary bodies can be obtained by superposition.

A particularly interesting problem is that of a lifting hydrofoil - or cascade of hydrofoils - and the resultant effect of the parameter γ upon the pressure distribution and circulation about the hydrofoil. As an example we quote the result of the lifting flat plate inclined at a small angle a to a parallel flow. The average speed of the parallel flow is therefore $U_o \exp(-\gamma x)$. The lift coefficient based upon pressure distribution when compared to a uniform flow is

$$\frac{C_L}{C_L(\gamma = 0)} = 1 - \frac{\gamma}{2}\ln\left(\frac{\gamma}{2}\right) - 0.654\gamma$$

for small values of the parameter γ, the reference velocity being U_o. This result is rather interesting in that the effect of channel contraction is not directly proportional to the parameter γ as might have been expected by considering only the effect of altered boundary conditions on the plate in an otherwise uniform flow.

Calculations of the flow past thin cambered hydrofoils with thickness in which the contraction effect is taken into account as indicated above have been carried out as part of a doctoral dissertation by Mr. R. Mani and will be presently submitted for publication.

Acknowledgment

It is a pleasure to express appreciation for the advice and friendly criticism of Professor Emeritus Aladar Hollander. The work referred to herein was made possible by the cooperation of many other members of the Hydrodynamics Laboratory staff. Among these, especial thanks are due to Messrs. J. Kingan and T. Kiceniuk. Finally, the writer would like to acknowledge publicly the support of the Office of Naval Research

TABLE I

List of Reports, Publications and Theses
Prepared Under Contract Nonr 220(24)

1. Nawoj, H. J., "Cavitation Studies in Axial Inducers", AE Thesis, California Institute of Technology, 1956.

2. Carpenter, S. H., "Performance of Cavitating Axial Inducers with Varying Tip Clearance and Solidity", AE Thesis, California Institute of Technology, 1957.

3. Acosta, A. J., "The Effect of a Longitudinal Gravity Field on the Supercavitating Flow over a Wedge", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.1, May 1958.

4. Acosta, A. J., "An Experimental Study of Cavitating Inducers", Proceedings of Second Symposium on Naval Hydrodynamics, Washington, D. C., August 25-29, 1958.

5. Acosta, A. J. and Hollander, A. H., "Remarks on Cavitation in Turbomachines", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.3, October 1959, presented at "Golden Jubilee Symposium on Hydraulic Machinery", Indian Institute of Science, Bangalore, 1959.

6. Sarosdy, L. R., "Cavitation-Simulating Studies in Water and Freon-113", AE Thesis, California Institute of Technology, 1960.

7. Sarosdy, L. R. and Acosta, A. J., "Note on Observation of Cavitation in Different Fluids," Trans. ASME, Series D, Vol. 83, p. 399, 1961.

8. Acosta, A. J. and Parkin, B. R., Discussion of "Scale Effects of Cavitation", by J. W. Holl, G. F. Wislicenus, Trans. ASME, Series D., Vol. 83, p. 385, 1961.

9. Acosta, A. J., "Cavitating Flow past a Cascade of Circular Arc Hydrofoils", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.2, March 1960.

10. Linhardt, H. D., "Application of Cascade Theories to Axial Flow Pumps", ME Thesis, California Institute of Technology, 1960.

11. Acosta, A. J., "The Effect of a Longitudinal Gravitational Field on the Supercavitating Flow over a Wedge", Trans. ASME, Series E, Vol. 28, p. 188, 1961.

12. Stripling, L. B. and Acosta, A. J., "Cavitation in Turbopumps, Part I", J. of Basic Engineering, Series D., Vol. 84, pp. 326-338, 1962.

13. Stripling, L. B., "Cavitation in Turbopumps, Part II", J. of Basic Engineering, Series D., Vol. 84, pp. 339-350, 1962.

14. Linhardt, H. D. and Acosta, A. J., "Note on the Application of Cascade Theory to Design of Axial-Flow Pumps", ASME Paper No. 62-WA-222, 1962.

15. Wade, R. B., "Flow past a Partially Cavitating Cascade of Flat Plate Hydrofoils", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.4, January 1963.

16. Acosta, A. J. and Wade, R. B., "Some Unsteady Effects in Cavitating Flow", California Institute of Technology Hydrodynamics Laboratory Film Report No. E-79.5, August 1963.

17. Wade, R. B., "Water-Tunnel Observations on the Flow Past a Plano-Convex Hydrofoil", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.6, February 1964.

18. Acosta, A. J., "Cavitation in Cascade", California Institute of Technology Hydrodynamics Laboratory Film Report No. E-79.7, presented at ASME Winter Annual Meeting, Chicago, November 7-11, 1965.

19. Wade, R. B., "Investigations on Cavitating Hydrofoils", PhD Thesis, California Institute of Technology, 1965.

20. Wade, R. B. and Acosta, A. J., "Experimental Observations on the Flow Past a Plano-Convex Hydrofoil", California Institute of Technology Hydrodynamics Laboratory Report No. E-79.8; also appeared as Paper No. 65-FE-3 in J. of Basic Engineering, 1965.

21. Wade, R. B., "Linearized Theory of a Partially Cavitating Plano-Convex Hydrofoil Including the Effects of Camber and Thickness", submitted to Journal of Ship Research, SNAME, 1965.

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13. ABSTRACT

This report describes work carried out in the general field of hydrodynamics of turbomachines under Contract Nonr 220(24). The principal objective was to understand the basic features of the flow in various types of turbomachines and where possible to use such results in the development of design theories. The major emphasis was placed upon problems of cavitation in axial machines and certain theoretical as well as experimentally related phenomena. Three projects were undertaken: The measurement and observation of cavitating flows in axial inducer pumps, the observation of cavitation and cavitation inception in fluids other than water, and the observation and measurement of forces on the vanes of a cavitating cascade in a water tunnel.

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